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Effects of Head Up Display Symbology Lag on Recovery from Inadvertent Instrument Meteorological Conditions: Performance Costs

By Arthur Estrada, Patricia A.
LeDuc, Siobhan M. Gallagher,
Joanna L. Greig, and Shannen
L. Dumond



Warfighter Performance and Health Division

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13. ABSTRACT (Maximum 200 words) Aviator workload reduction efforts have led to the production of head up displays (HUD) for the Aviator's Night Vision Imaging System (ANVIS). These devices superimpose flight symbology on one tube of the ANVIS so that no head movement is required to obtain flight information. Recent advances in technology have given the HUD a faster processing time than its first versions. This study examined the effects of symbology lag time on pilot recovery from inadvertent entry into instrument meteorological conditions (IMC) using HUD1 (refresh rate of 750-1000 milliseconds) and HUD3 (refresh rate of 19-39 milliseconds), and serves to show the performance cost of using systems with slower refresh rates. HUD3 more closely approximates the real environment and out-performed HUD1 in several measures.				
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Table of contents

	<u>Page</u>
Introduction.....	1
Background	1
Objectives.....	1
Methods.....	1
Subjects.....	1
Procedure.....	2
Data analysis.....	3
Results.....	3
Demographics.....	3
Flight experience and recovery from IIMC.....	3
HUD version: crashes and recoveries.....	4
Control reversal errors.....	6
Bank excursions.....	7
Flight profile effects.....	9
Discussion and conclusions	10
References	12

List of figures

1. Mean recovery times by HUD version.....	5
2. Example of roll reversal error from a left bank	6
3. Example of the range of maximum angles of bank during recovery.....	8
4. Range of maximum angles of bank by HUD version.....	9

List of tables

1. Flight demographics of study participants.....	3
2. Mean flight experience relative to recovery results.....	4
3. HUD version of flights ending in a crash.....	4
4. Time from IIMC to crash.	5
5. Frequency of roll reversal errors by HUD version.....	7
6. Frequency of recoveries and crashes by flight profile.....	9

Introduction

The past three decades of technological advances in U.S. Army aviation have provided the capability to fly nap-of-the-earth (NOE) missions at night. The technology that has enabled Army pilots to gain this operational advantage is the head-mounted illumination intensification device called the Night Vision Goggle (NVG) (Collins and Piccione, 1998). Further workload reduction efforts have led to the production of a head up display (HUD) for the Aviator's Night Vision Imaging System (ANVIS), a current version of the NVG. This device superimposes flight symbology on one tube of the ANVIS so that no head movement is required to obtain flight information. It is believed that this addition has helped decrease aviator workload during flight. However, past research has shown that some aviators actually experience more severe episodes of spatial disorientation while using the HUD (Durnford et al., 1995).

Background

The ANVIS/HUD system receives critical flight data from aircraft sensors (altitude, airspeed, attitude, torque, compass heading, etc.) and transmits the data to the NVGs. The data are overlaid on the NVG imagery to provide the pilot with integrated night scene and critical flight data symbology. Research has noted that some individuals perform better than others with these constructed visual environments due to different experience levels (Lampton, Bliss, and Morris, 2002). The system uses a cathode ray tube (CRT) to display flight symbology. The symbology images are generated by modulating the intensity of a scanning electron beam striking a phosphor coated surface. The electron beam, focusing coils, deflection plates, and phosphor are encapsulated in a glass envelope (tube). CRTs provide a bandwidth and resolution (limited) that are compatible with the eye's requirements for high quality imagery (McLean, 2001).

Extended lag times involved in the presentation of dynamic visual information has been shown to degrade visual tracking performance, introduce image artifacts, and promote motion sickness (Moffit, 1997; Kalawsky, 1993; Biocca, 1992). Performance degradations have resulted from decrements in system fidelity or mismatches in the constructed environment when it does not closely approximate the real environment (Hix and Gabbard, 2002). Recent advances in technology have given the HUD a faster processing time than its first version. The first version (HUD1) had a processing/turnover time or "refresh rate" of 750-1000 milliseconds. In other words, displays of critical changes in aircraft attitude could be received by the pilot up to one second late. A second HUD version offered an improvement of one-third to one-half the original, with a refresh rate of about 300 milliseconds. The third version (HUD3) can process at a range of about 19 to 39 milliseconds (Richman, 11 Jan 00; Richman, 27 Jan 00).

Objectives

This study examined the effects of symbology lag time on pilot recovery from inadvertent entry into instrument meteorological conditions (IMC) using HUD1 and HUD3, and serves to show the performance cost of using systems with slower refresh rates.

Methods

Subjects

Twenty UH-60-rated Army aviators were recruited from Fort Rucker, Alabama, to act as volunteer subjects. There were no age, rank, or gender restrictions.

Procedure

Informed consent was obtained from each volunteer prior to participation. A brief questionnaire was given to determine the number of flight hours each pilot had in the UH-60, using any HUDs, using NVGs, and total flight hours. All flights were conducted in the U.S. Army Aeromedical Research Laboratory's NUH-60 flight simulator that features computer-generated visual displays and a multi-channel data acquisition system to facilitate analysis of various parameters of flight such as attitude, heading, airspeed, and altitude control. Before flying the data collection flights, participants were permitted a 10-minute flight in order to familiarize themselves with the handling qualities of the flight simulator and the HUD symbology.

For data collection, each participant flew two different nighttime flight profiles for each version of the HUD (HUD1 and HUD3), resulting in a total of four flights per volunteer and a total of 80 flights from which data were collected. The order of HUD versions was randomized and the maximum symbology display was used for all flights. A 15-minute break was given between flights to allow the HUD versions to be changed.

Both flight profiles required the volunteers to follow a computer-generated lead aircraft through a mountain valley which required multiple left and right banks in order to stay in the proper trailing position. At a predetermined point during each flight, the simulator operator obscured the outside visual scene by changing the simulator visibility from three statute miles to zero statute miles in an instant. Such an event necessarily prompted the volunteer to execute a recovery from inadvertent entry into instrument meteorological conditions (IIMC). The recovery procedures followed were those learned and practiced by all Army UH-60 pilots and are listed in the Army's Aircrew Training Manual (Department of the Army, 2005). The specific steps are:

- a. Attitude – level the wings on the attitude indicator
- b. Heading – maintain heading; turn only to avoid known obstacles or as briefed for multiship operations
- c. Torque – adjust torque as necessary
- d. Trim – trim aircraft as necessary
- e. Airspeed – adjust airspeed as necessary

To ensure that the volunteer used HUD symbology to obtain aircraft status information for the recovery, aircraft instrument panel lights were turned off in synchrony with the IIMC event rendering the instruments unusable in the dark. In order to successfully recover from the IIMC, pilots had to reference the HUD in order to obtain aircraft status information. The two

flight profiles differed in that the IIMC in one flight occurred while the aircraft was in a right bank, while the other occurred while the aircraft was in a left bank. The flight ended when the recovery was complete (operationally defined as the instant the volunteer maneuvered the aircraft to an altitude of 2000 feet, a heading of 360 degrees, and airspeed of 120 knots) or when the aircraft was crashed.

Throughout each flight, the computer collected a variety of measures such as specific headings, altitudes, airspeeds, angles of bank, and other flight parameters. These digitized flight performance data were collected and stored on a VAX computer system for subsequent statistical analyses.

Results

Demographics

Descriptive statistics for the sample of these 20 aviators indicated a wide range of experience levels (Table 1).

Table 1.
Flight demographics of study participants.

	Minimum	Maximum	Mean	Std. Deviation
Total Flight Hours	600	9800	2751.00	2203.960
Total NVG Hours	22	1120	498.35	357.112
Total HUD Hours	3	450	52.05	98.063

Flight experience and recovery from IIMC

Analyses showed no statistically significant differences in the recovery results or times when flight experience (total, NVG, and HUD) was considered. While not significant, some observations deserve comment. Three subjects crashed twice, six crashed once, and eleven never crashed. Table 2 presents descriptive statistics of the sample's flight experience as it relates to the success of their recoveries. Note that the average total flight experience of those producing the least number of successful recoveries was lower than the average flight experience of those who were more often successful (in bold). When NVG and HUD experience is considered, however, this observed relationship lacks consistency even when outliers are removed.

Table 2.
Mean flight experience relative to recovery results.

	N	Hours of flight experience (mean, min/max, std deviation)	Hours of NVG experience (mean, min/max, std deviation))	Hours of HUD experience (mean, min/max, std deviation)
Subjects with 2 out of 4 recovery attempts ending in a crash.	3	833 600 – 1100 251.66	84 22 – 180 84.00	18 5 – 30 12.58
Subjects with 1 out of 4 recovery attempts ending in a crash.	6	3008 750 – 5100 1406.56	637 150 – 1120 365.33	115 10 – 450 168.14
Subjects with 0 out of 4 recovery attempts ending in a crash.	11	3134 600 – 9800 2631.21	536 120 – 1100 331.08	27 3 – 80 26.32

HUD version: crashes and recoveries

Of the 80 flights conducted, 12 (15%) resulted in crashes. A general review of the crashes indicates that those aviators using HUD1 crashed twice as many times as those using HUD3 (8 and 4 crashes, respectively) (Table 3). In other words, subject aviators crashed 20 percent of the time when trying to recover using HUD1 compared to 10 percent using HUD3. Although notable, this difference did not achieve statistical significance [$\chi^2(1, N = 12) = .545, p = .460, \tau = .045$]. A closer examination of the crash data reveals that, in fact, three of the 20 volunteers were responsible for half of all the crashes, crashing two out of their four flights. One of the individuals crashed twice during recovery attempts with HUD1, while the other two crashed once with each HUD version.

Table 3.
HUD version of flights ending in a crash.

		HUD Version		Total
		HUD 1	HUD 3	
Flight Profile	Recovery attempted from a left bank	7	4	11
	Recovery attempted from a right bank	1	0	1
Total		8	4	12

For the unsuccessful recovery attempts, an inspection of the time from IIMC to actual impact was performed. Analyses indicate that the difference in HUD versions made a statistically significant difference [$t(10) = -2.283, p = .046$]. The data indicate that, on average, those aviators equipped with HUD3 were able to continue their attempts at recovery longer before crashing than those using HUD1 (49 vs. 24 seconds, respectively) (Table 4).

Table 4.
Time from IIMC to crash.

HUD Version	Mean	N	Std. Deviation
HUD1	23.63	8	12.68
HUD3	48.75	4	26.48

The remaining 68 flights (85%) resulted in successful recoveries. The mean recovery time of those using HUD1 (166 seconds) was greater than the mean recovery time of those using HUD3 (137 seconds) (Figure 1). Although noteworthy, the 29-second difference did not achieve statistical significance [$t(66) = 1.95, p = .056$].

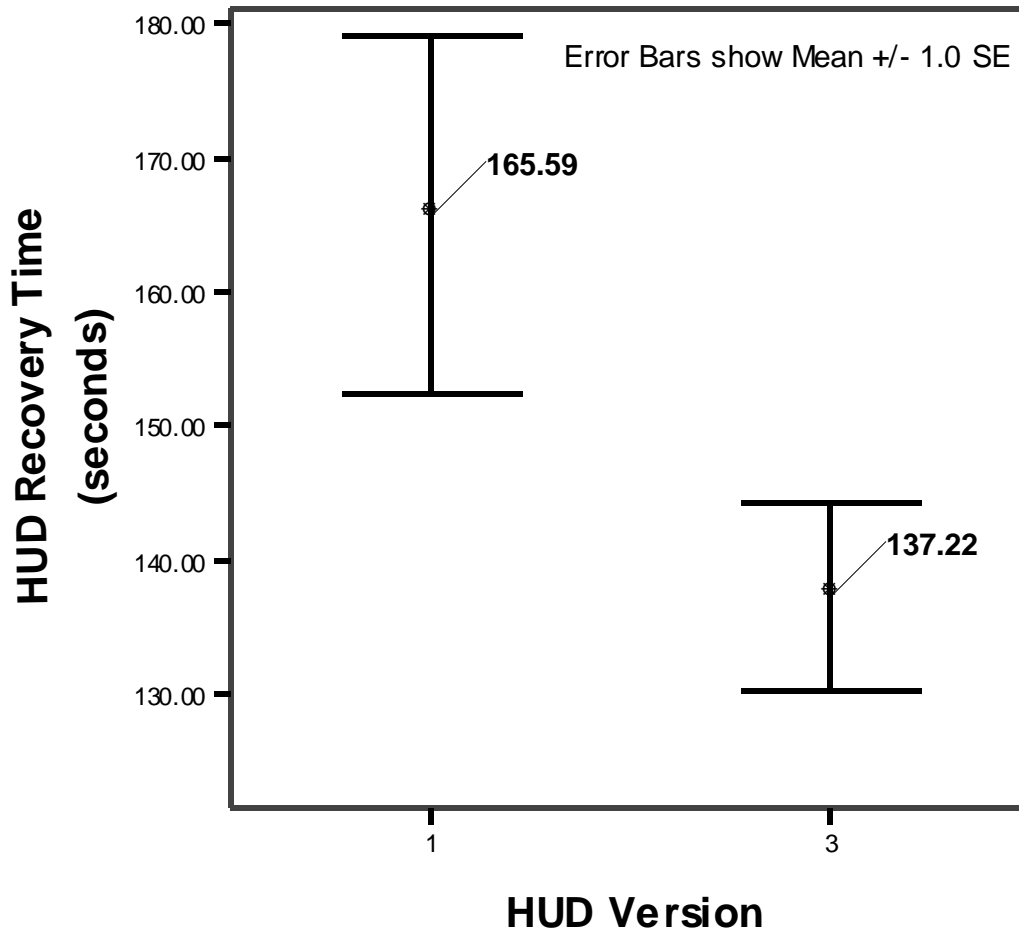


Figure 1. Mean recovery times by HUD version.

Control reversal errors

A control reversal error (CRE) occurs when the pilot moves the control in a manner so as to increase an undesirable situation rather than in a direction to decrease the undesirable situation (Liggett and Gallimore, 2002). A reversal error in the roll axis is usually caused by a misinterpretation of bank attitude (Previc and Ercoline, 2004) and is characterized by initially increasing the bank angle while attempting to return to level flight (Hasbrook and Rasmussen, 1973).

For this study, the first 15 seconds of roll data following the onset of IIMC was examined to assess whether there was evidence of any roll reversal errors. Pilot cyclic control movements could not be examined as they were not in the original data collection design plan. Therefore, aircraft roll fluctuations were used as manifestations of control inputs and used to detect CREs. A roll reversal error was noted to have occurred whenever the angle of aircraft roll (bank) was increased by the pilot in the same direction as the bank at the onset of IIMC (Figure 2). An increase in the roll attitude in the same direction indicates that the pilot's action was contrary to the required action of leveling the aircraft pursuant to a successful recovery and established recovery procedures. (Recall that the first step of recovery is to level the wings on the attitude indicator.)

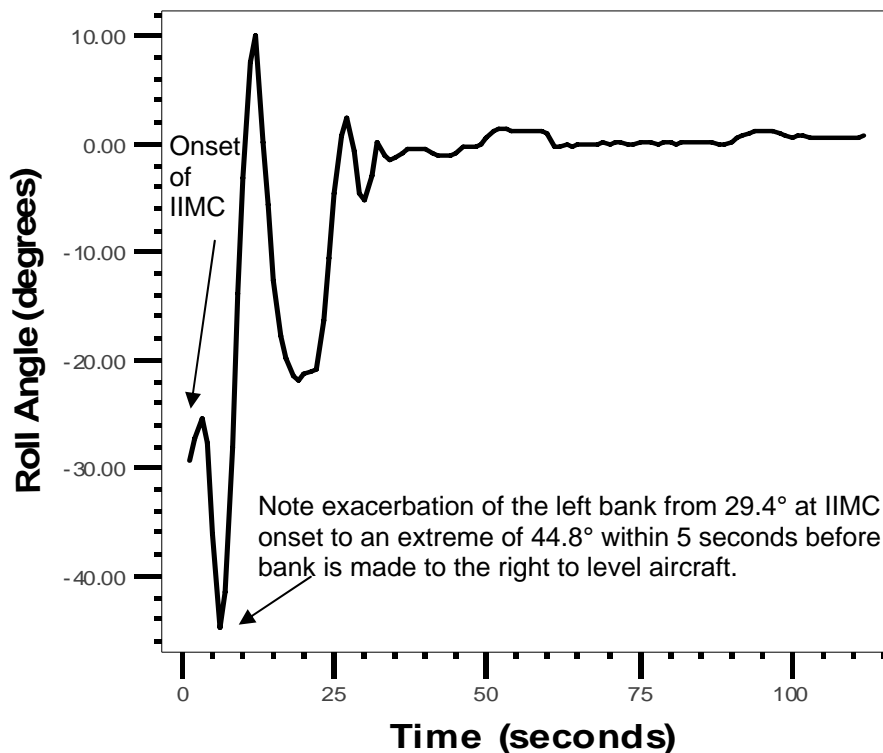


Figure 2. Example of roll reversal error from a left bank.
(negative degrees = left bank angle; positive degrees = right bank angle)

An examination of these data showed that the HUD version made no significant difference in the occurrence of roll reversal errors [$\chi^2(1, N = 80) = .802, p = .370$] (Table 5). However, further analysis revealed that the prevalence of roll reversal errors was significantly correlated (negatively) with total flight experience [$r(78) = -.242, p = .031$]. Hence, the more total flight experience, the less likely an aviator was to make a reversal error. Other experience factors (NVG and HUD) demonstrated no significant correlations ($p = .211$ and $p = .500$, respectively).

Table 5.
Frequency of roll reversal errors by HUD version.

		HUD Version		Total
		HUD 1	HUD 3	
Reversal Error	Yes	17	21	38
	No	23	19	42
Total		40	40	80

Bank excursions

In addition to detecting CREs, the range of bank excursions from left to right limits, and vice versa, were examined for the first 60 seconds following IIMC to determine if symbology refresh rates affected the range of excursions during recovery attempts. During recoveries, pilots attempt to level the aircraft by adding control inputs which result in aircraft banks from one side to the other. Attitude indications presented via the HUD symbology are only as accurate as the last symbology refreshment, therefore, during recovery attempts, pilots may be responding to HUD attitude displays that are up to 1 second old (in the case of HUD1). In effect, without real-time indications, the pilot must estimate the magnitude of the input necessary to level the aircraft. The inherent delay of the real-time attitude information results in bank excursions (overshoots) left and right as the pilot narrows his/her banks to achieve the desired level attitude. The magnitude of these overshoots, caused by over-controlling, can produce banks in the opposite direction which are as severe and as potentially hazardous as the banks from which the recoveries are attempted. An examination of the range of maximum angles of bank from right to left or vice versa during the recovery attempts offered an indication of the HUD's effectiveness at providing the pilot with the needed attitudinal situation awareness (Figure 3).

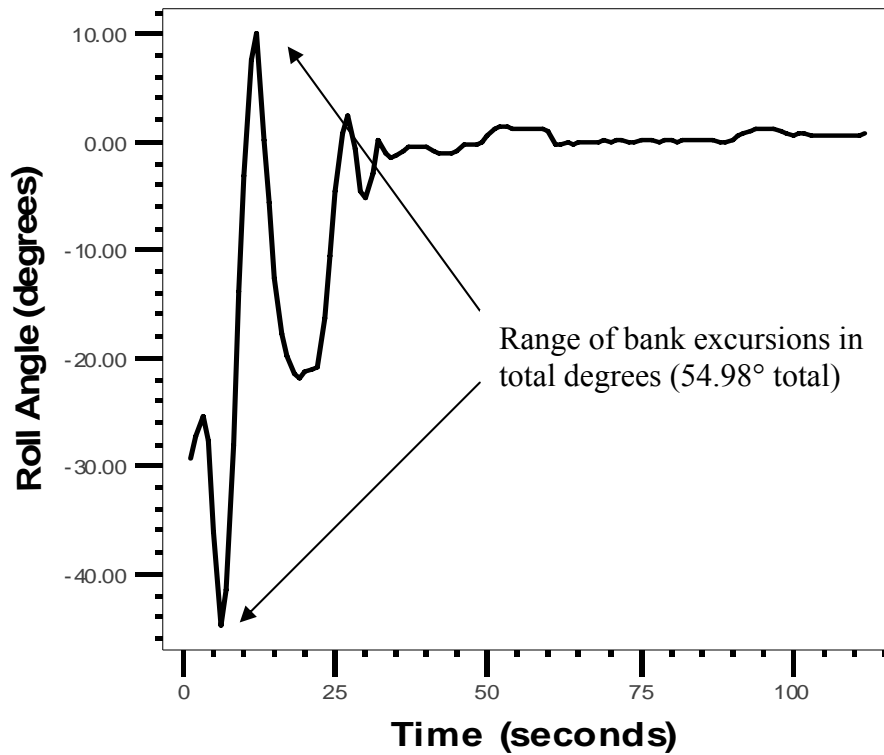


Figure 3. Example of the range of maximum angles of bank during recovery.
(negative degrees = left bank angle; positive degrees = right bank angle)

A review of these data shows that the HUD version made a significant difference [$t(78) = 2.79, p = .007$] when the range of maximum angles of bank was considered. HUD3 produced, on average, excursions of less magnitude than HUD1 (Figure 4).

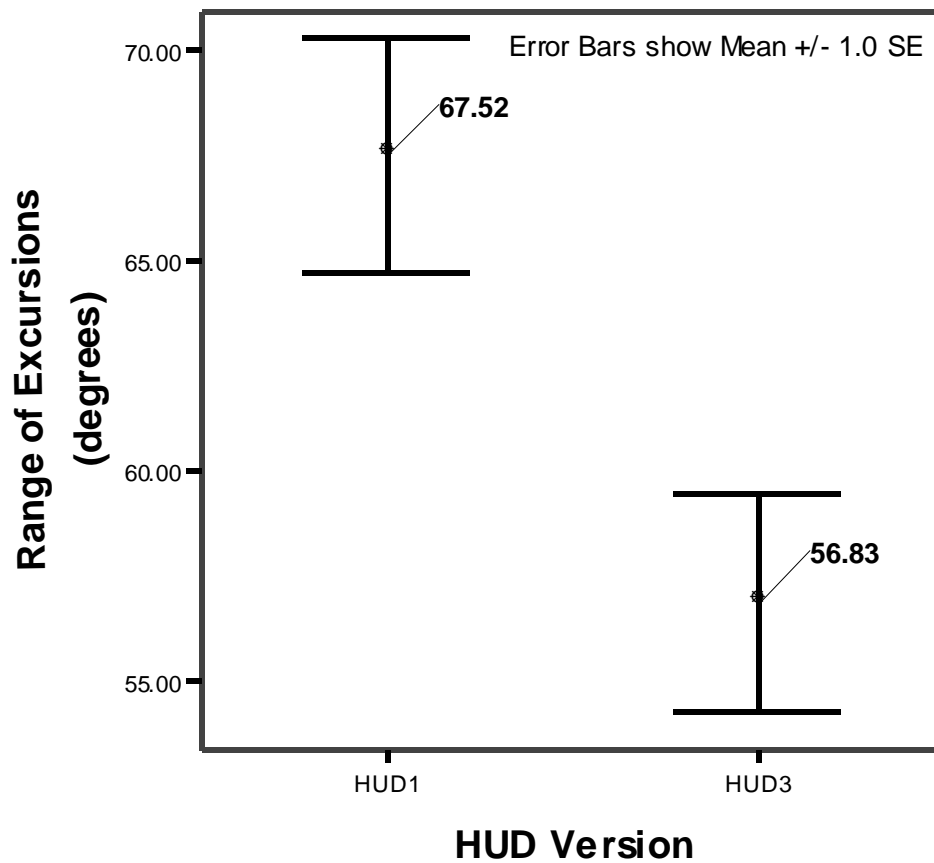


Figure 4. Range of maximum angles of bank by HUD version.

Flight profile effects

Table 6 shows that 11 participants crashed as a result of entering IIMC during a left bank, while only one aviator crashed while trying to recover from a right bank. This was a statistically significant difference [$\chi^2(1, N = 80) = 9.804, p = .002$].

Table 6.

Frequency of recoveries and crashes by flight profile.

		Flight Result		Total
		Recovered	Crashed	
Flight Profile	Recovery attempted from a left bank	29	11	40
	Recovery attempted from a right bank	39	1	40
Total		68	12	80

Discussion and conclusions

The results of this study support our hypotheses. HUD3, with its faster refresh rates, more closely approximates the real environment and, as such, out-performed HUD1 in all measures where the HUD version was shown to be a factor:

- a. Flights ending in a crash (HUD3: 4 vs. HUD1: 8)
- b. Mean time attempting recovery before a crash (HUD3: 49 seconds vs. HUD1: 24 seconds)
- c. Mean time to full recovery (HUD3: 137.22 seconds vs. HUD1: 165.59 seconds)
- d. Mean ranges of maximum angles of bank (HUD3: 56.83 degrees vs. HUD1: 67.52 degrees)

This study found no significant correlations between flight experience (total, NVG, and HUD) and performance relating to recovery results and mean recovery times from IIMC. However, it is noted that pilots who experienced one or more crashes had relatively less total flight experience than those who successfully recovered all four flights, regardless of HUD version used.

The reason that a significantly larger number of crashes (11) occurred when recovery was attempted from a left rather than a right bank (1 crash) was initially puzzling. A consensus of research pilots offered a plausible explanation. Any helicopter with a counterclockwise-rotating rotor system is more responsive (moves faster) from a left bank to level than from a right bank to level. (Note that although this study was conducted in a flight simulator, the flight characteristics of the device emulate that of the actual aircraft.) The reason involves the aerodynamic characteristics of the advancing side of the rotor disk versus the retreating side. The advancing side is on the right side of the disk in a forward flying helicopter. As the aircraft is rolled from a left to right, the angle of attack is increased due to the airflow from below which results in greater lift and maneuverability along the longitudinal axis. On the other hand, a roll from right to left (in leveling the aircraft) has the opposite effect on the advancing side, slowing the rolling action. Therefore, it is reasonable to speculate that recovery attempts made in a faster manner contribute to over-controlling the aircraft and overshooting the desired level attitude, especially when using delayed symbology as the primary attitude reference.

This study serves to demonstrate the performance costs of using a slow system versus a faster system. (Note that HUD1, with the slower of the two refresh rates used in this study, is no longer used in the field.) The use of a constructed informational display like the ANVIS-HUD can influence performance in negative ways. In the operational environment, such consequences can be deadly. The faster the refresh rate of displayed data, the less apt system users are to experience these difficulties. New display symbology is currently being researched to aid in instrument landings within desert brownout conditions (Walker, 2003). Additionally, it has been suggested that future helmet-mounted systems may employ full-immersion virtual reality displays (Rash, 2001). Potential performance decrements produced by high processing demands and suboptimal refresh rates must be investigated during the design phase to avoid adverse consequences that may result after fielding. The findings of this effort provide direction for

future research and development relating to faster refresh rates of electronically-presented flight symbology. The closer the image approximates the dynamic, real-time environment, the higher the expectations for human performance and mission success.

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